01 Jan 1998

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Recommended Citation

N. H. Maerz and W. Zhou, "Optical Digital Fragmentation Measuring Systems -- Inherent Sources of Error," *Fragblast*, vol. 2, no. 4, pp. 415-431, Taylor & Francis, Jan 1998.
The definitive version is available at https://doi.org/10.1080/13855149809408786

Maerz, N. H., and Zhou, W., 1998. **Optical digital fragmentation measuring systems - inherent sources of error.** FRAGBLAST, The International Journal for Blasting and Fragmentation, Vol. 2, No. 4, pp. 415-431.

Optical digital fragmentation measuring systems – inherent sources of error

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ABSTRACT: Automated optical imaging systems of measuring fragmentation are increasingly being used in the mining, comminution, and materials handling industries. These methods have been well received in many of the industries involved. Considering that in many of these applications there are no alternative ways of sizing material, having even a rudimentary measurement of size distributions allows evaluations of explosive, blast design, detonator performance, crusher and milling performance, and material degradation due to transport.

Optical methods have inherent limitations, which reflect on accuracy, precision, and reproducibility of measurement results. This stems from the fact that there are myriads of variables, which affect the outcome of the measurements. Errors start with the imaging process, which may distort the reality because of the scale of observation, may induce sampling bias, and may simply not return a good representation of the reality. More errors are introduced in the digital processing stage, where blocks may be miss-identified. The reconstruction of three-dimensional distributions from measured two-dimensional distributions of partially-overlapped, fines-censured images can introduce further errors.

Understanding of these limitations provides the key to the successful use of optical image systems. Understanding of what can and cannot be measured and the relative accuracy's makes these systems useful. Defining realistic acceptable levels of error is also necessary. This paper seeks to clarify these issues, and to quantify them from laboratory studies wherever possible.

KEYWORDS: fragmentation, optical, image analysis, measurement, and errors.

1. INTRODUCTION

Optical methods of analyzing fragmentation (Figure 1) were first proposed by Carlson & Nyberg, (1983), and developed into a workable methodology by Maerz et al. (1987a; 1987b). Since then, a proliferation of measurement systems have been described in the literature, including research tools (Nie & Rustan 1987, Paley et al. 1990, Ducet & Lizotte 1992, Stephansson et al 1992, Montoro & Gonzales 1993, Haverman & Vogt 1996, Girdner et al. 1996) and commercially available systems (Palangio et al. 1995, Maerz et al. 1996, Dahlhielm 1996, Schleifer & Tessier 1996, Downs & Kettunen 1996, Kleine & Cameron 1996, Chung & Noy 1996). Franklin et al. 1996 have given a brief history of the evolution of measuring systems.

Whereas the standard of measurement is currently defined by sieving, optical methods are inevitably compared to sieving. The advantages of optical systems are numerous:

1. The measurements can be completely automated, eliminating the expense of a human operator, and the associated subjectivity.

2. Many more measurements can be made, consequently increasing statistical reliability by reducing sampling errors.

3. No interruption of production processes is required, and results are available in a very short time, allowing adjustments to production methods.

4. Screening is just too prohibitive in the case of large assemblages of rock or in the case of applications requiring very large blocks such as the evaluation of armorstone.

Recently, optical methods have come under criticism for proported lack of accuracy, inability to measure fines, and other various perceived deficiencies (Cunningham 1996a). In part these criticisms are justified, as is explained in this paper, and indeed, under some conditions optical methods achieve very poor results.

However there are many applications where results have justified the use of optical systems. Published applications using the WipFrag system include the following:

1. Selbay Mine, Joutel, Quebec, Canada, has optimized their blasting performance, monitoring energy consumption, loading rates, payloads of haulage trucks, secondary blasting costs, and maintenance costs as a function of fragment size (Palangio et al. 1995).

2. INCO's Coleman Mine, Sudbury, Ontario, Canada, was able to expand their blasting pattern by 40%, with cost saving of up to 80%, while actually improving the degree of fragmentation (Palangio et al., 1995)

3. Highland Valley Copper, Logan Lake, British Columbia, Canada, have been able to correlate their mill tonnage with the feed size, paving the way to greater production by optimizing feed size (Simkus and Dance 1998).

4. Bartley and Trousselle (1998) were able to show a direct relationship between accurate detonators and improved fragmentation.

This paper assesses the typical errors with optical systems, using a variety of screened gravel sized materials (Figure 2), analyzed by the WipFrag image processing package.

2. SOURCES OF ERROR

2.1 Introduction: Definition of errors

Errors should not be thought of as "mistakes" but as a measure of the variability between the measured results and the "true" value of the parameter being measured, as there is an error involved with any measurement technique.

This brings up the question as to what is the "true" value. In many cases, not the least of which is measuring a size distribution of a large assemblage, the true value is impossible to measure, because each measurement method has associated with it an error that may or may not be well defined. Consequently "true values" are typically defined by the established method of measurement, and there is the perception that new methods must conform to the existing standard.

2.2 What you see is what you get

One of the principle provisions of image based systems is that they can only measure what appears on the image. Consequently more accurate results are obtained from good, clear images, taken at an appropriate scale of observation. Less accurate results are obtained from haphazard photography, for example, using low resolution imaging equipment, or poor lighting, or an inappropriate scale of observation.

It therefore follows that if an appropriate image of an assemblage of rock cannot be taken, accurate measurements should not be expected, and indeed many applications are not conducive to imaging techniques.

The errors related to optical systems can be considered in four distinct classes:

1. Errors related to the method of analysis of the images.
2. Errors related to sample presentation.
3. Errors related to the imaging process.
4. Errors related to sampling processes.

2.3 Errors related to the method of analysis of the images

Block misidentification from color and texture characteristics

Because most imaging systems key in on the shadows between fragments, using these to delineate individual blocks, highly textured or multicolor fragments tend to confuse the block delineation algorithms, resulting in falsely identified fragment edges, and conversely missing fragment edges. This has been termed disintegration and fusion (Eden & Franklin 1996).

In terms of color characteristics, the lighter the color of the rock, the easier it is for the edge delineation algorithms to correctly identify the edges. Even though this is true, it is still possible to image materials of all colors from white quartzite to black coal. Problematic are mixed color assemblages, where there are fragments of different color densities. In these cases fragment delineation can be poor. Equally problematic are assemblages where individual fragments exhibit mottling, or color density variations. These typically also result in poor fragment delineation.

Surface texture on the fragments also tends to confuse the edge delineation algorithms, in the same way that color differences do. In addition, fragments with void spaces are often difficult to deal with.

The situation is made worse in the case of washed and wet fragments, as this highlights color differences. Experience with WipFrag has shown that in these cases best results are obtained where a fine coating of dust obscures these color or textural differences. Consequently it is usually best to image the fragmentation before they are washed, or wet screened. In other cases better results may be obtained from washed specimens.

Errors of edge misidentification are best expressed in terms of the fidelity of the network of block outlines generated by the algorithm, when overlaid and visually compared to the original image. In a study using the WipFrag system on a minus 3/8’ yellow pea gravel distribution, error levels were measured by comparing a near perfect manually edited network to a series of less perfect networks, generated automatically using a variety of edge detection parameters. The tendency was for the automatically generated nets to overestimate the measure of central tendency D_{50} (size with 50% by weight passing) by up to 33%, and underestimate the variability (average slope of the curve) by up to 34%. However, when judgment was used to visually select the most representative net, the errors were only 17% and 9% respectively.

Wrong unfolding model

Optical imaging systems measure in two dimensions, because images are two-dimensional. Typical systems measure either block areas or block cross sections. To model the fragmentation realistically, the two-dimensional measured distribution must be transformed into a representative three-dimensional one. This process of reconstructing a three dimensional distribution is known as unfolding. An example of some unfolding methodologies are given by Maerz (1996a). It has been suggested that unfolding need not be done, and the two dimensional measurements should simply be used (Cunningham 1996b). This could indeed be considered correct where measurements are used as comparisons only, as the unfolding function is merely a mathematical transformation. However it is intuitively more satisfying to present three-dimensional numbers.

While it is clearly desirable to have the best model possible, the errors from using a less accurate model are most likely slight, when compared to many of the other types of errors. In addition, they are systematic, i.e. they will always overestimate or underestimate by a fixed proportion. Consequently these can be completely eliminated by empirical calibration.

2.4 Errors related to sample presentation

Fragment lay

There is a fundamental difference between what is measured by optical imaging systems and by a screening system. Putting aside for the moment the requirement made of imaging systems to measure blocks in place, i.e. in partially overlapping assemblages, the difference is one of what is being measured.

Assuming anisotropic block shapes, and making the assumption the blocks tend to lay flat, it is clear that imaging systems will tend to measure the major and intermediate diameters of the block. On the other hand, sieves will measure the minor and intermediate axis (Wang & Stephansson 1996).

As a result of this, optical systems will tend to give larger measurements than sieving, simply because the two methods are measuring different parts of the same fragment.

A simple simulation can demonstrate this. If we consider a group of 8 idealized elliptical fragments, with axis length ratios of 1:1:1, 1:1:2, 1:1:3, 1:2:2, 1:2:3, 1:3:3, 2:2:3, and 2:3:3, we can predict how these would be measured by sieving and by an optical system, providing no overlap. The results are demonstrated in Table 1. Average actual block diameter is taken simply as the arithmetic mean of the major, intermediate, and minor diameters. Sieving diameter is taken as the intermediate diameter. Imaging diameter is taken by using the elliptical area of the largest surface (area = $\pi ab/4$), where a and b are taken as the major and intermediate diameters, and using a circular area equivalent diameter (diameter = $[4*\text{area}/\pi]^{1/2}$).

Results of this analysis show that for individual blocks, sieving errors can be as high as ±67%, while for imaging the error can be as high as +67%. If the errors are averaged in this “highly idealized assemblage” consisting of a single block of each shape, the over and underestimates in the sieving results cancel each other out, while the imaging process overestimates by an average of 26%. This is however somewhat misleading, as true assemblages would not contain the full range of block shape ratios, but would rather tend to be composed mostly of one or several shapes.

What follows from this is that we can expect imaging systems to overestimate size measurements, when compared to sieving method, the degree of which depends on the shape of the fragments. This can be compensated for by empirical calibration, assuming the fragment shape is constant. Alternatively, if shape can be measured, analytical or statistical compensation may be possible.

Block Shape Ratio	Actual Average Block Diameter	Simulated Sieving Diameter	Simulated Imaging Diameter	Sieving Error %	Absolute Sieving Error %	Imaging Error %
1:1:1	1	1	1.00	0	0	0
1:1:2	1.33	1	1.41	-33	33	8
1:1:3	1.67	1	1.73	-67	67	6
1:2:2	1.67	2	2.00	33	33	33
1:2:3	2.00	2	2.45	0	0	45
1:3:3	2.33	3	3.00	67	67	67
2:2:3	2.33	2	2.45	-33	33	12

2:3:3	2.67	3	3.00	33	33	33
Mean	1.88	1.88	2.13	0	33	26

Table 1: Simulated measured average diameters of idealized elliptically shaped blocks from sieving and imaging.

Overlapping fragments

The expectations for optical systems are that they are required to measure fragment sizes in situ, that is to say, in muckpiles, stockpiles, conveyor belts, etc., where the individual fragments are typically partially overlapped by other fragments. With sieving methods, on the other hand, fragments are "handled" individually.

Consequently if images of partially overlapped fragments are analyzed without taking into consideration the effect of the overlap, the size distribution will be underestimated.

The use of a statistical transformation, for example one based on principles of geometric probability, can be used to remove this error (Maerz 1996a), making the assumption that the nature or the degree of overlap is somewhat constant.

Experience with WipFrag suggests an underestimation of about 28% in such a case. In a study with a uniform sample of screened gray crushed limestone, 3588 fragments were imaged and measured individually (no overlap), with a resulting mean diameter of 10.5 mm. When mixed in an assemblage of partially overlapping fragments, the apparent (uncorrected) mean diameter was measured to be 7.6 mm, a 28% underestimation. When the standard WipFrag unfolding transformation was applied, the (corrected) mean diameter was found to be 11.1 mm, a much smaller error, which is a slight overestimation of about 6%.

2.5 Errors related to the imaging process

Sampling window

When an image taken of an assemblage of fragments with a relatively wide distribution, not all sizes of fragments present will be distinguishable in a single image. At the extreme, some boulders may be larger than will fit into the image, while some smaller fragments will just be too small to be seen on the image. More practically, very large fragments that do fit on an image, and very small fragments that are barely perceptible on an image may not be easily measured by the block detection algorithm, because of their extremes in size.

Santamarina & Fratta (1996) point out that the imaging process becomes a "bandpass filter" resulting in recognition of fragments in a specific bandwidth of size only. In practice this bandpass filtering effect tends to be a lowpass filtering effect because, imaging is typically and intuitively set at an appropriate scale to include the largest block if it is visible. The difficulty lies more at the other end of the spectrum where the small fragments or fines in a typically wide distribution tend not to be imaged. This results in an overestimate of fragment size, and can be thought of as a type of sampling error.

This has dire consequences for the potential to accurately evaluate wide distributions using optical methods. Experience using WipFrag has shown that optical imaging works best within a distribution that ranges about 1 order of magnitude, i.e., where the largest block is no large then 10 times the size of the smallest. The theoretical limit of resolution is about two orders of magnitude, i.e., where the largest block is 100 times the size of the smallest. The effective operating range of an optical system on a single image is somewhere in that range, and depends on image resolution, and on the resolution of the edge detection algorithms.

Errors created by this effect are difficult to quantify and can range from very small in the case of a screened and scalped distribution, to an error of about 50% in the D_{50} in the case of typical blast fragmentation with a Rosin-Ramler slope (N) of about 1.0.

There is no good way to eliminate this type of error for wide distributions, although there are some practical solutions as to how to deal with these problems (Maerz, 1996b).

The first solution involves using the measured values as they are. Given that the errors are systematic it is not difficult to rationalize the use of optical systems for a relative comparison, understanding that the error in measured values may be large in comparison to true values, but relative errors will be low.

The second solution involves using an empirical calibration. Experience with WipFrag has indicated that empirical calibrations depend only on the shape of the distribution (e.g., Rosin-Ramler N value). Thus, if the shape of the distribution of the two fragment assemblages are the same, the same empirical calibration can be applied regardless of the relative sizes of the two distributions.

The final solution is the use of a zoom-merge technique, where images are taken at different scales of observation and the results are merged into a single analysis (Santamarina et. al.; 1996, Franklin et. al; 1995).

CCD camera variability

Images from CCD (charge coupled device) cameras show statistical variability in the intensity values imaged for each picture element (pixel). Although this is not apparent to the human eye because of the rather limited ability of the eye to distinguish fine changes in intensity, it is however significant with respect to the typically 256 levels of intensity digitized by most systems.

Because block delineation algorithms tend to be sensitive to the patterns and shapes of light and dark areas on the image, results of the analysis of multiple images, especially images of poor quality will be variable. Where the images are of good quality and the fragment outlines are unambiguous, the results will be less affected.

Results from WipFrag testing indicates a typical variability of +/- 0.38% at a 95% confidence level for the pea gravel distribution and +/- 0.54% for the gray limestone crushed rock sample, using the D_{50} parameter. These errors are not significant.

Lighting variability

Variability in lighting intensity can result in block delineation errors in the same manner as with CCD camera variability. Most cameras have amplifiers built in, and most digitizing boards also have integrated amplifiers as well, so the lighting variability is somewhat buffered. However, amplification of a relatively weak video signal also results in amplification of the inherent noise caused by the variability in the CCD.

Variability in the structure of the lighting also can result in block delineation errors. Since the block delineation algorithms key in on the shadows between blocks, there is an optimum amount of shadow for optimum block delineation. If the lighting is too flat, e.g., overcast day, the shadows between blocks may be too weak and some may be too hard to detect. If the lighting is highly directional and comes from a low angle source, the shadows may be too strong, and some small blocks may be obscured.

This type of error is difficult to quantify, as it depends not only on the lighting conditions, but also on other factors such as the quality of the image. It is recommended that for critical applications, such as conveyor belts, a constant source of artificial lighting be installed and the dynamic effects of natural lighting be blocked.

Perspective

An image free of perspective distortion needs to be taken where the axis of the camera is perpendicular to a somewhat planar surface of fragments. Perspective errors occur when the surface of an assemblage is imaged at an oblique angle, or when the surface of fragments deviates significantly from planar.

Clearly, the best solution is to take the images from an orthogonal perspective, wherever possible. It has been shown that perspective errors are dramatically reduced by using long focal length (telephoto) lenses (Maerz, 1996b). This is however not always possible, especially in confined space such as underground.

WipFrag provides an option to do a geometric rotation on oblique images for short focal length lenses. Test results on rotated images of square ruled paper show that the error caused by oblique imaging can be removed by a geometric transformation of the image (Figure 3).

There is however a second source of error involved here. The ability to make corrections by geometric rotations works well on idealized images. In reality one side of the image, before rotation, will be at a different scale than the other side of the image, and the resolution of that side of the image may be too low.

2.6 Errors related to sampling

Of all the errors that an optical system can encounter, the most significant are sampling errors.

Sampling errors are problematic for any type of measurement process. For examples, for sieving analysis, sampling errors result because vast quantities of materials need to be characterized, while only a small quantity of material can actually be measured. The more uniform the material, the less significant this error. If the material is non-uniform, then errors occur depending on how and where the material is sampled.

For optical systems there are two potential sources of sampling errors, both relating to spatial segregation of material.

Segregation of materials

Assemblages of granular material are rarely found in a state where there is no segregation if different sizes are represented. Even if at some point in a production process they are not segregated, the materials handling processes soon start segregating the material. Fine fragments drop out of sight into the void space between coarser fragments, especially if helped by the vibration on a conveyer belt. Material dumped from a truck is initially coarser, and nearer the end of the load finer. Material rolling off a stock pile tends to roll further if is it coarser.

From the viewpoint of optical systems there are two issues here. First, there is variability of where the image is taken, e.g., at the top of a muckpile, at the side, in a stockpile, etc. This type of error is impossible to quantify generally, as the amount of segregation can be highly unpredictable, but the potential magnitude of the error is very large, larger than the errors from any of the other processes discussed in this paper. With optical systems this kind of error can be overcome by measuring all of the material rather than measuring material at a selected few locations. This is particularly easy to do by imaging on a conveyor belt, if all the material passes along that belt.

The second type of segregation relates to the fact that optical systems see only the surface of an assemblage of material. If there is segregation, such as the fines falling in and behind the coarser fragments, this will not be measured by optical systems. However, for a given point along a particular process, such as a fixed distance along a conveyor moving at a fixed rate of speed, receiving a constant feed, the amount of segregation may be fairly constant and an empirical calibration may prove useful.

3 ACCURACY AND PRECISION

3.1 Acceptable levels of errors

Just as the amount of error in size measurements varies with the type and emplacement of material to be measured, the acceptable level of error varies widely with the intended use of the measurement.

At the one extreme is a measurement for the purposes of meeting specifications, such as an aggregate material, which has a very narrow acceptable size distribution. That specification can be measured with a fair degree of accuracy using sieving methods (in the case of non-elongated particles), although studies indicate that sieving tends to overestimate the variability of the distribution

(Syvitski et al. 1991), and is known to be sensitive to shape effects (Matthews, 1991). The intended use of that measurement is to determine if a very small sample meets those specifications.

Although optical systems could undoubtedly meet this precision were fragments handled and imaged individually, the intended use of an optical system might be to measure sizes continuously and without disrupting the production stream. As such, the fragments are imaged in a partially overlapped context and the measurement errors would, in many cases, most likely exceed the acceptable level of error in the material specification.

At the other extreme are measurement applications in larger materials, such as riprap or armorstone, where there is no alternative to optical methods. Screening is not possible because of the size of the material. In this case larger errors are acceptable.

There are many applications that fall between the two extremes. Blast fragmentation may be screened at great expense and time, but can easily be measured using an optical system at nominal expense. Some degree of error is acceptable in this case.

Finally, processes such as blasting can be characterized by looking at the relative differences between two measurements, and consequently the absolute error is not important. A process such as crushing can be characterized by monitoring the change in fragment size over time, and consequently the absolute error is again not important.

4.2 Accuracy

Accuracy is defined as the difference between the measured valued and the “true” values. The true value of a size distribution is an elusive quantity. Given that sieving is the traditional standard of measuring size distribution, it is often taken as the true value. However as there is variability even in sieving measurements, it is still not an ideal way to measure true value.

Optical methods, because of the requirement to measure in situ partially overlapped blocks, will tend to result in raw measurements that are too small, and because of the fact that fines may not be seen in the image, will tend to result in measurements that are too large. As a result, the measurement could be too small or too large, but the net effect is typically a measurement that is too large.

Of necessity then, accuracy for optical systems can be achieved only by using calibrated solutions. The calibration could be analytical or empirical, but typically depends on the assumed shape of the distribution. Consequently, because the solution is calibrated, the accuracy thereof is really a function of the precision of the measurement, and the applicability of the calibration.

For some distributions, such as scalped, highly uniform crushed rock distributions, a calibration may not be required, and the accuracy can be determined directly

4.3 Precision

Precision, as opposed to accuracy is a measure of repeatability. This is a quantity that is much easier to measure than accuracy.

Tests were conducted using the WipFrag system to determine the minimum size differences that could be discriminated, by increasing and decreasing the camera objective distance to simulate changes in block size. Results show that for single images the minimum discrimination can be as high as 8% (Figure 4). Using replicates (multiple images) the discrimination can be as low as 2% with as little as 10 images.

In a similar test the objective distance was changed in a systematic way to simulate larger and smaller assemblages, starting with differences of 2% then 4% then 6%, etc. (Figure 5). The results of this test show the ability of the system to discriminate, but it also indicates that as the scale of observation deviates from the baseline, so does the relative accuracy of the measurement.

4.4 Verification

Analysis of a medium graded crushed limestone aggregate found errors of less than 10% in the D_{50} measure with respect to sieving results, without the benefit of calibration (Maerz, 1990).

Analysis of the yellow pea gravel resulted in an overestimation of the D_{50} parameter by 20% without calibration. With calibration, assuming a Rosin-Ramler n value of 3.0 (highly uniform), resulting D_{50} values were found to be within 4% of sieving values.

Field trials, conducted for the United States Bureau of Mines revealed D_{50} valves were within 2-16% of the screened results for many of the analyses when adjustments were made for missing fines (Maerz, 1990).

Recent tests were conducted by Noranda to evaluate three different image based granulometry systems (Liu and Tran, 1996). In these tests no calibration or operator intervention was permitted, only automated measurements. The raw WipFrag measurements were found to be the closest to the sieved results. Afterwards, using a standard calibration curve, the D_{50} values measured by WipFrag came within 2% of sieving results (Rosin-Ramler n value of 1.5, average uniformity).

5. CONCLUSIONS

5.1 Measurement potential of optical systems

The measurement of granular assemblages is and has always been problematic. For assemblages larger than sand sized, sieving has traditionally been the only method of measurement. While sieving can result in very accurate and repeatable measurements under certain conditions, it does however have significant drawbacks:

1. Sieving or screening is simply not economically feasible for large sizes such as riprap or armorstone. Even for smaller sizes, such as routine blast fragmentation, the costs in time and effort are prohibitive.
2. For sizes such as sand and gravel, only a very small proportion of the material can be measured using sieving. The costs to do a statistically valid number of samples are prohibitive, unless the material is extremely uniform.
3. In the case of on-line processes, sieving may require disruption of production to take samples, and the analytical results are not available quickly enough to make real time adjustments to the on-line processes.
4. With fragile material, the sieving procedure can actually further break down the material, returning an inaccurate size distribution.
5. Sieving is essentially a measure of the intermediate diameter of fragments, so measurement errors for flat and elongated materials could be large (from a weight, volume, maximum dimension, or average dimension perspective).

Optical systems, despite any drawbacks have certain inherent advantages:

1. The absolute size of the material being measured is irrelevant. It makes no difference if an image is of boulders, or of microscopic particles.
2. It is relatively easy to do enough analyses to get a statistically significant number of samples. Optical systems can make individual measurements in seconds rather than hours, thus large numbers of measurements are not only possible, but also cost effective.
3. Optical systems are designed to analyze images in place on conveyor belts. Because the material does not need to be handled separately, there is no disruption of the production process. Because the analysis is so fast, real time adjustments can be made to the production equipment.
4. Also because there is no additional handling involved, there will be no degradation of fragile materials. Consequently, such things as ammonium nitrate prills can be measured without being damaged.

5. Optical systems measure the average diameter of the visible part of the fragment. Thus, an elongated particle will tend to be classified according to the average of the longer and shorter diameter.

5.2 Errors in optical systems

This paper has shown that using optical systems can result in measurement errors when compared to sieving measurement. These errors, however, must be put in context, in the sense that the optical and sieving measurements really do measure two different aspects of fragments size, as the former measures the intermediate and short diameters, and the latter measures the long and intermediate diameters. In addition, optical systems make measurements without handling individual particles, i.e., looking at surface images containing partially overlapped blocks.

Errors caused by individual factors have been quantified in this paper wherever possible. Experience with the WipFrag system has shown that the most significant errors in optical systems are sampling errors.

While some individual errors can be quantified, not all can. Overall, there is a tendency for optical systems to overestimate the central tendency of size distributions, and to underestimate the variability. These types of errors depend on the shape of the distribution, and range from negligible in narrow distributions (uniform material) to very large in wide distributions (well graded materials). This stems from the fact that the range of sizes present in wide distributions cannot be seen in a single image.

This type of error is in general systematic, and is a function only of the shape of the distribution. Consequently, in many applications an empirical calibration can be applied to greatly reduce the error. Since the calibration is dependent only on the shape of the distribution, and if it can further be assumed that the shape of the distribution is somewhat constant, the calibrated solution can be very useful.

5.3 Rationalization

From the research shown in this paper, it is evident that optical methods of determining size distributions are not for all applications. Ultimately there are some limitations; the most serious of which include rock types that image poorly, and wide (well graded) distributions where the fines are two small to be seen in the image.

Despite these difficulties, there are myriad's of applications where optical measurements can or are being used. The potential for the use of inexpensive continuous monitoring is enormous, and will only increase in the future.

The key to successful utilization of this technology involves understanding the types of errors and understanding what your measurements can and cannot do. Building on the measurements that can be successfully done will result in optimization of many types of processes.

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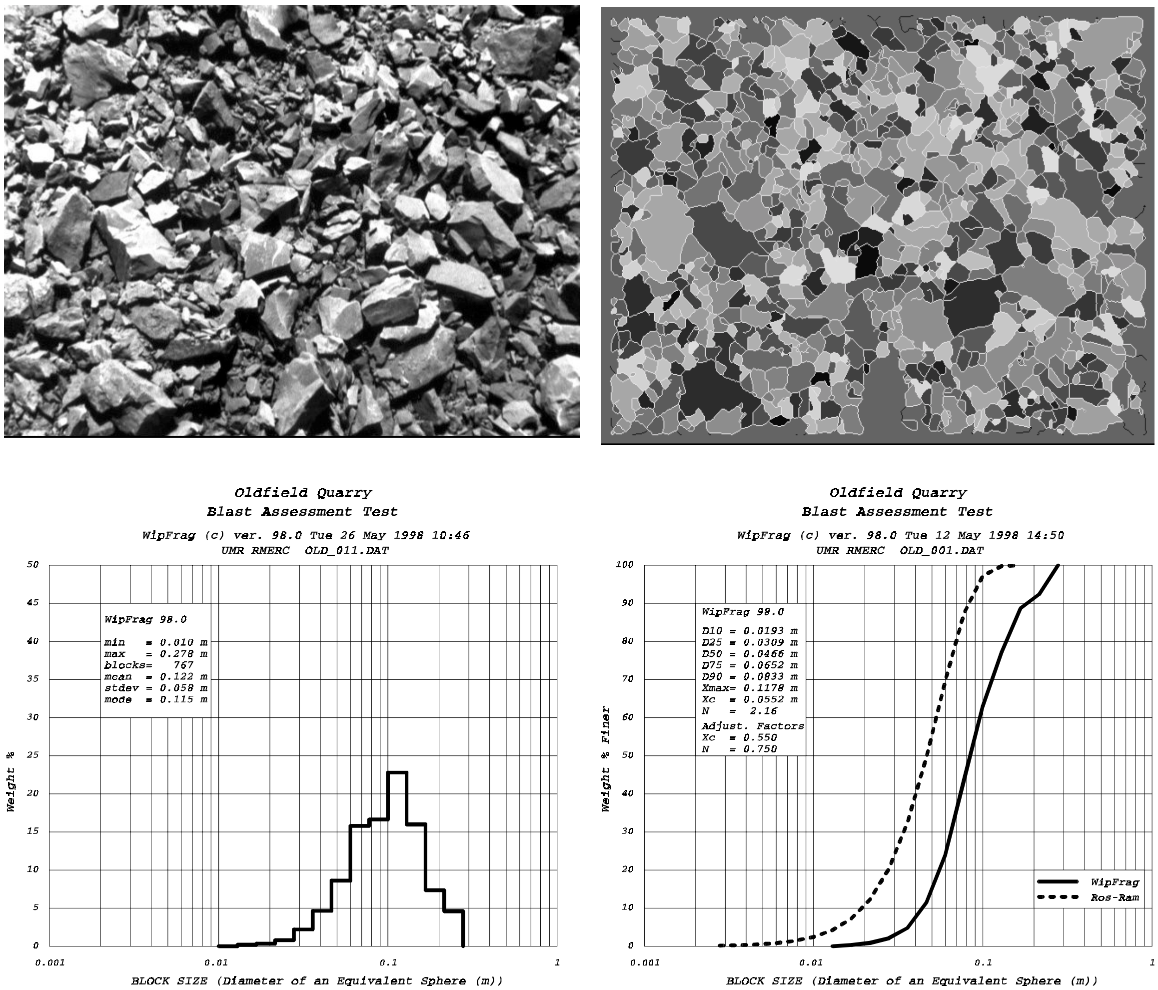


Figure 1. Top right: Typical image of rock fragmentation. Top left: Computer generated block outlines. Bottom right: Measured Histogram. Bottom left: Cumulative weight percent distribution, with calibrated curve (dashed line).

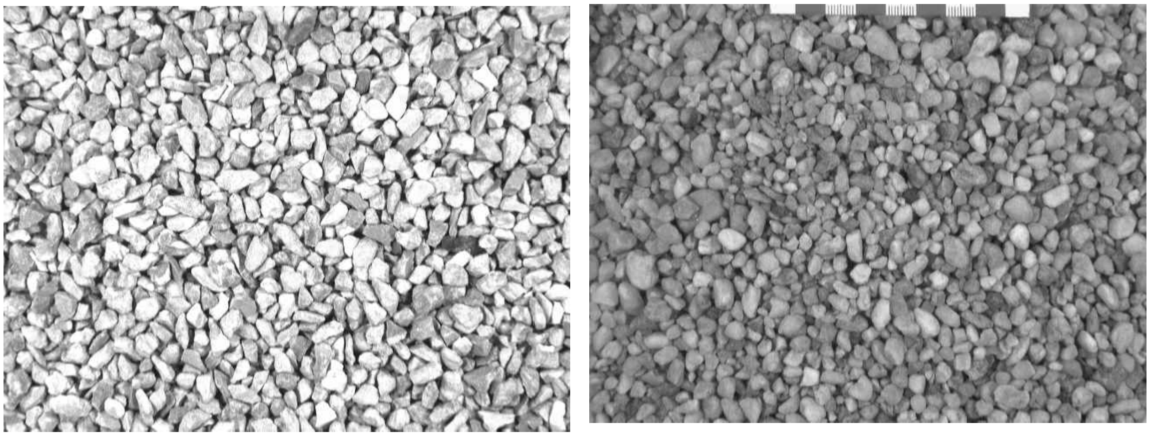
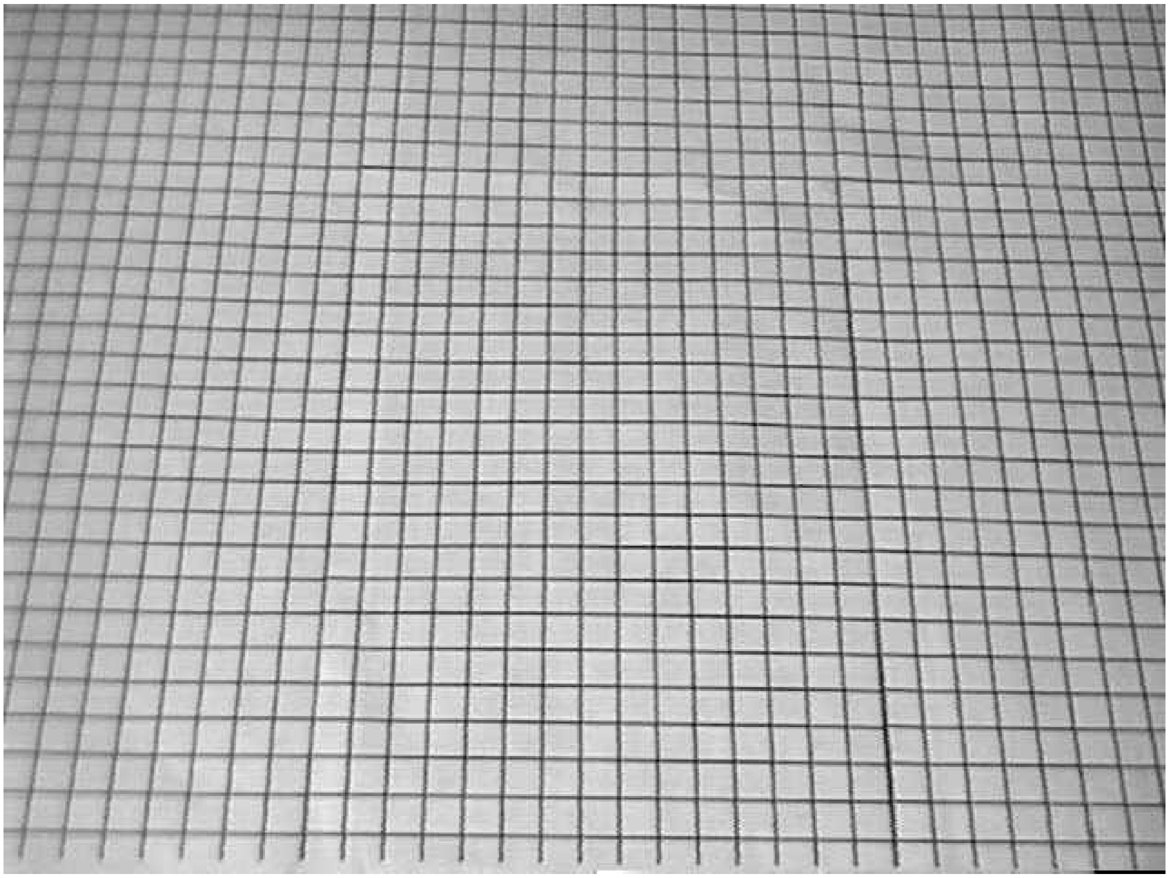


Figure 2. Aggregate samples used for testing. Right: Gray gravel. Left: minus 3/8" yellow pea gravel.



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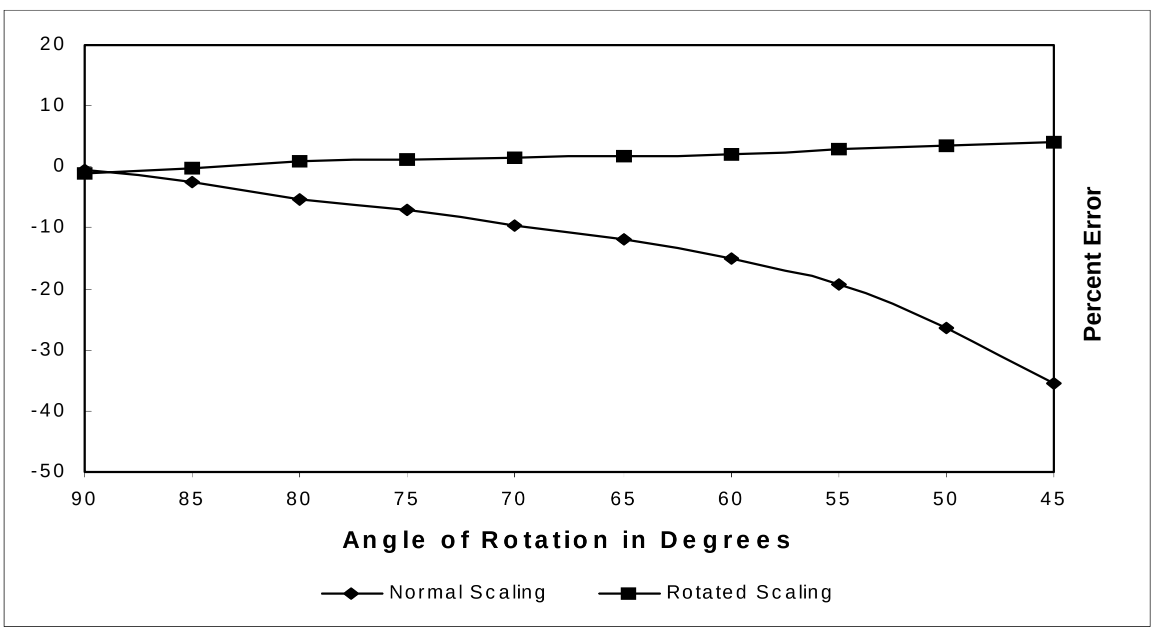
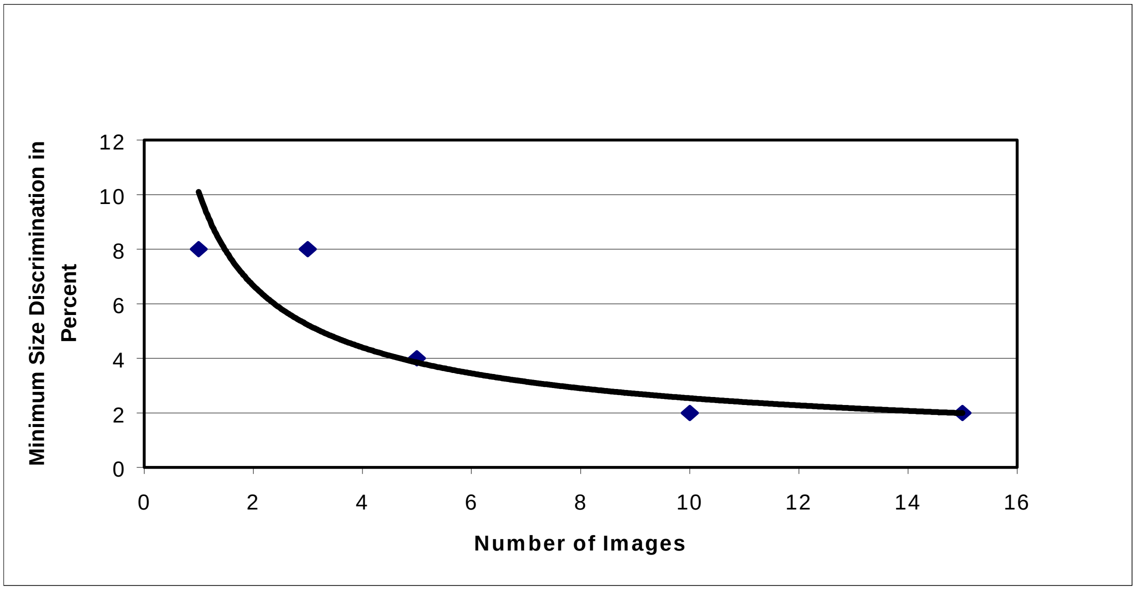


Figure 3 (top) Grid used for testing rotation algorithms. Figure. 3 (bottom). Errors on rotated images of squared paper with and without geometric correction.



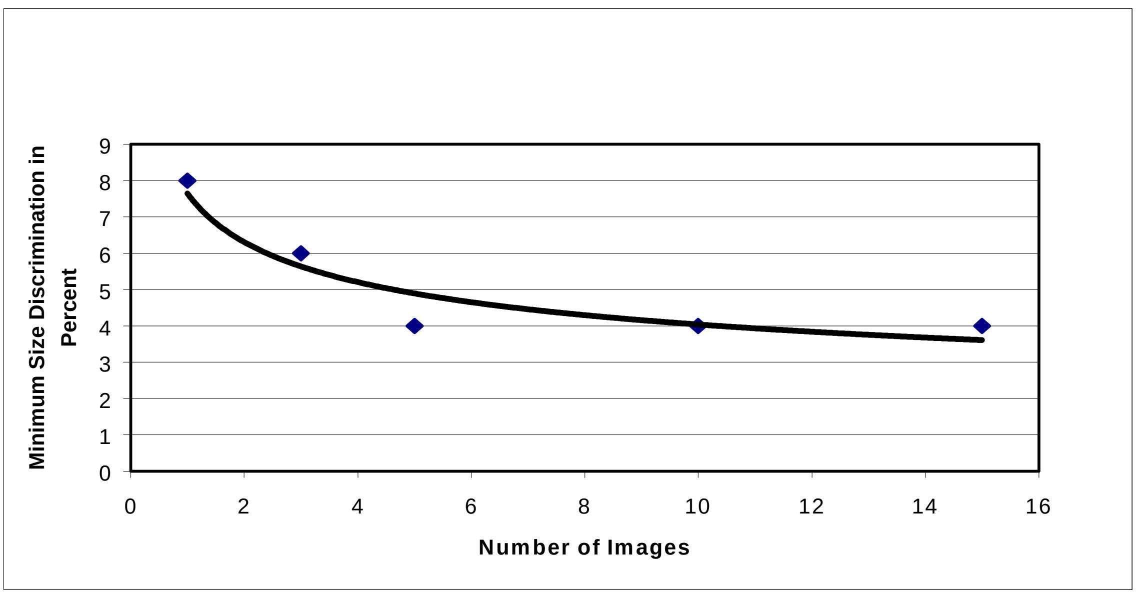


Figure 4. Relationship between the minimum size differences that can be measured as a function of the number of replicates for gray gravel (top) and yellow pea gravel (bottom).

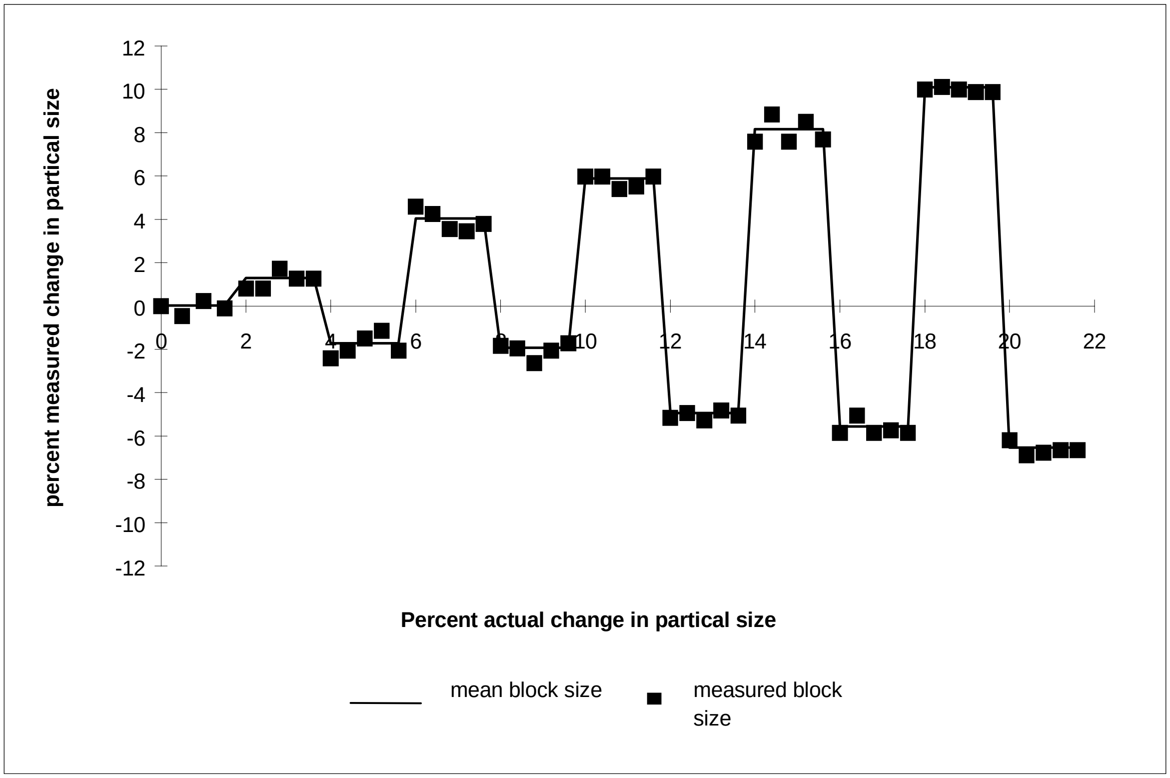


Figure 5. Graph showing the relationship between the simulated block particle size and the measured particle size. Simulation was conducted by changing the objective distance between the camera and assemblage to simulate smaller and larger assemblages, 0, +2%, -4%, +6% etc.